Advanced Concepts, Part 1

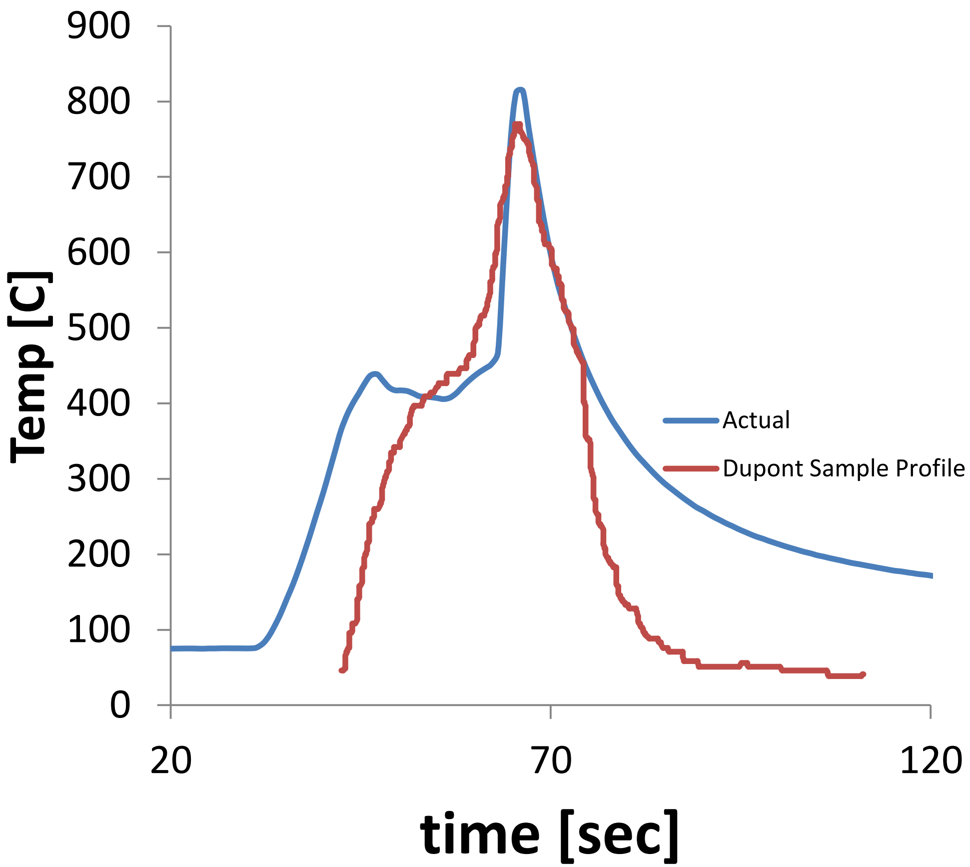
Lecture 15 – 11/3/2011

MIT Fundamentals of Photovoltaics 2.626/2.627

Joseph T. Sullivan

Cells are done!

Contact Firing



LAB

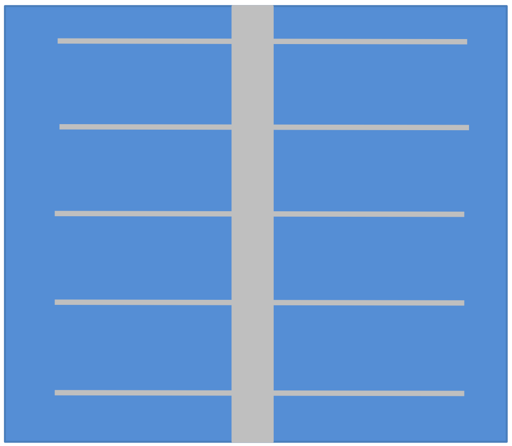
Please see the lecture 15 video for lab equipment visuals.

MPTC

INDUSTRY

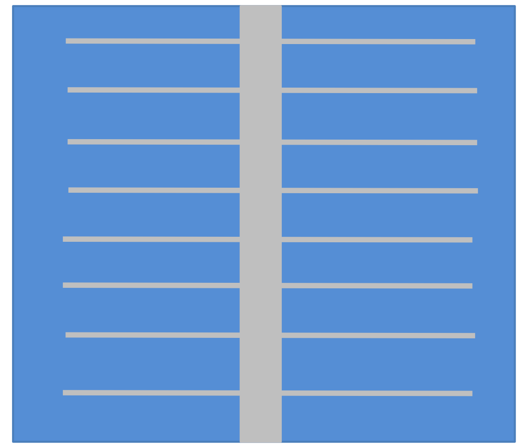
Torrey Hills

Effect of Shadowing Losses



4mm spacing

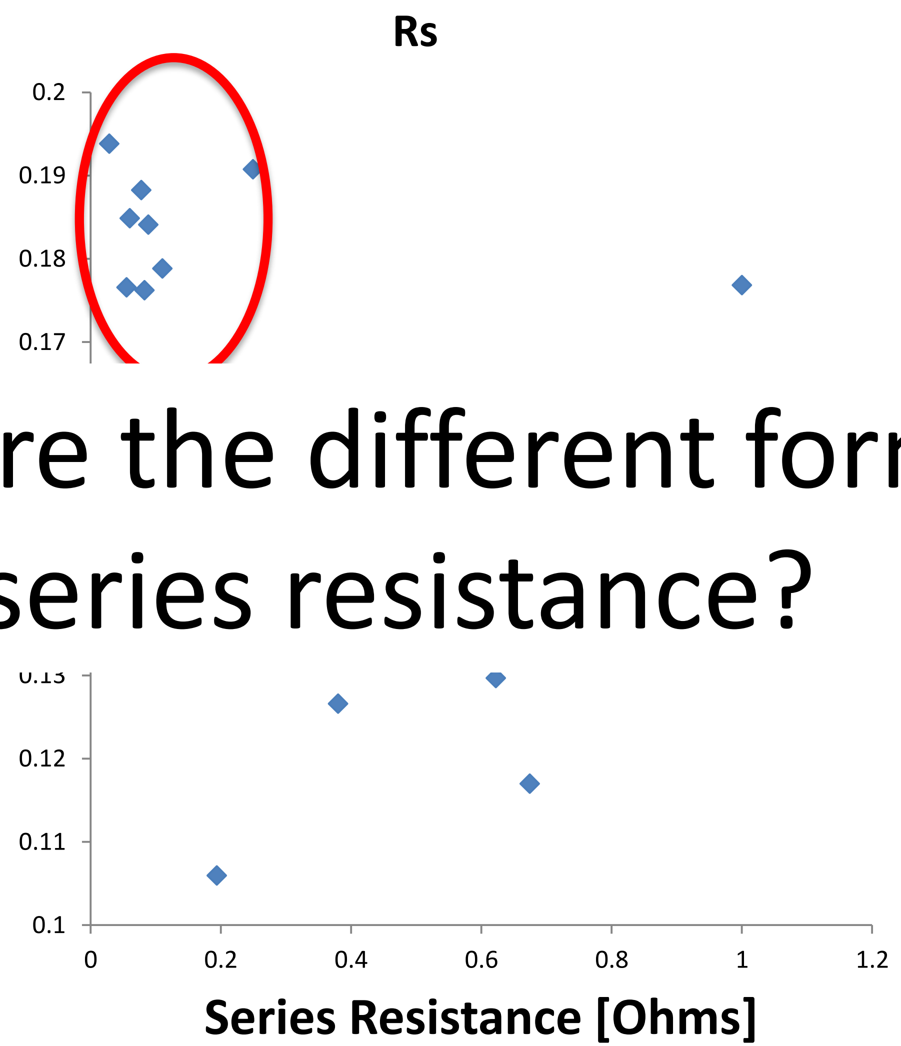
I_{SC} = 0.62A



2mm spacing

I_{SC} = 0.60A

What's Limiting Performance?



What are the different forms of series resistance?

Performance in the Field: Temperature, Shading, and Mismatch

Why Temperature Matters

- Solar cell efficiency measurements are performed at 25°C
- Most Semiconductor simulations occur at 300K (27°C)
- Typical Solar Cell operate at 50-65°C

Effect of Temperature

Recall:

$$I = I_L - I_0\left(\exp\left(\frac{qV}{kT}\right) - 1\right)$$

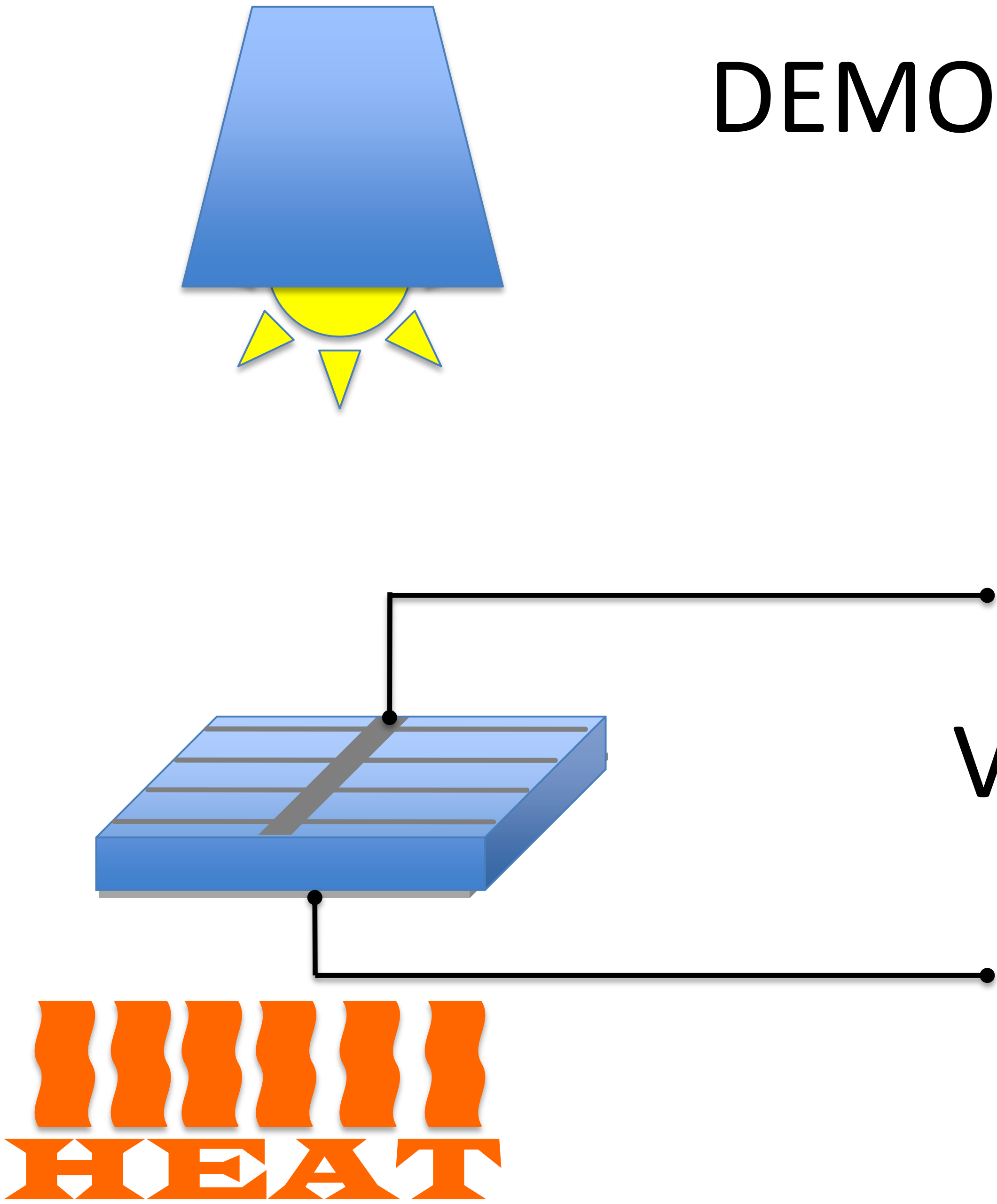
$$\downarrow$$

$$I_0 = \frac{qADn_i^2}{LN_D}$$

What do you think will happen with V_{oc} with temperature?

Source: PV CDROM

DEMO!



V_{oc}

V_{oc} Decreases with Temperature

$$V_{OC} = \frac{kT}{q}\ln\left(\frac{I_{SC}}{I_0}\right) = \frac{kT}{q}[\ln I_{SC} - \ln I_0] = \frac{kT}{q}\ln I_{SC} - \frac{kT}{q}\ln\left[B'T^{\gamma}exp\left(-\frac{qV_{G0}}{kT}\right)\right]$$

$$= \frac{kT}{q}\left(\ln I_{SC} - \ln B' - \gamma\ln T + \frac{qV_{G0}}{kT}\right)$$

$$\frac{dV_{OC}}{dT} = \frac{V_{OC} - V_{G0}}{T} - \gamma\frac{k}{q}$$

$$\frac{dV_{OC}}{dT} = -\frac{V_{G0} - V_{OC} + \gamma\frac{kT}{q}}{T} \approx -2.2mV\ per\ ^{o}C\ for\ Si$$

Courtesy of PVCDROM. Used with permission.

***Where $V_{G0} = qE_{G0}$, where E_{G0} is the band gap at absolute zero

0.09V decrease if operating at 65°C!

Source: PV CDROM

Effect of Temperature

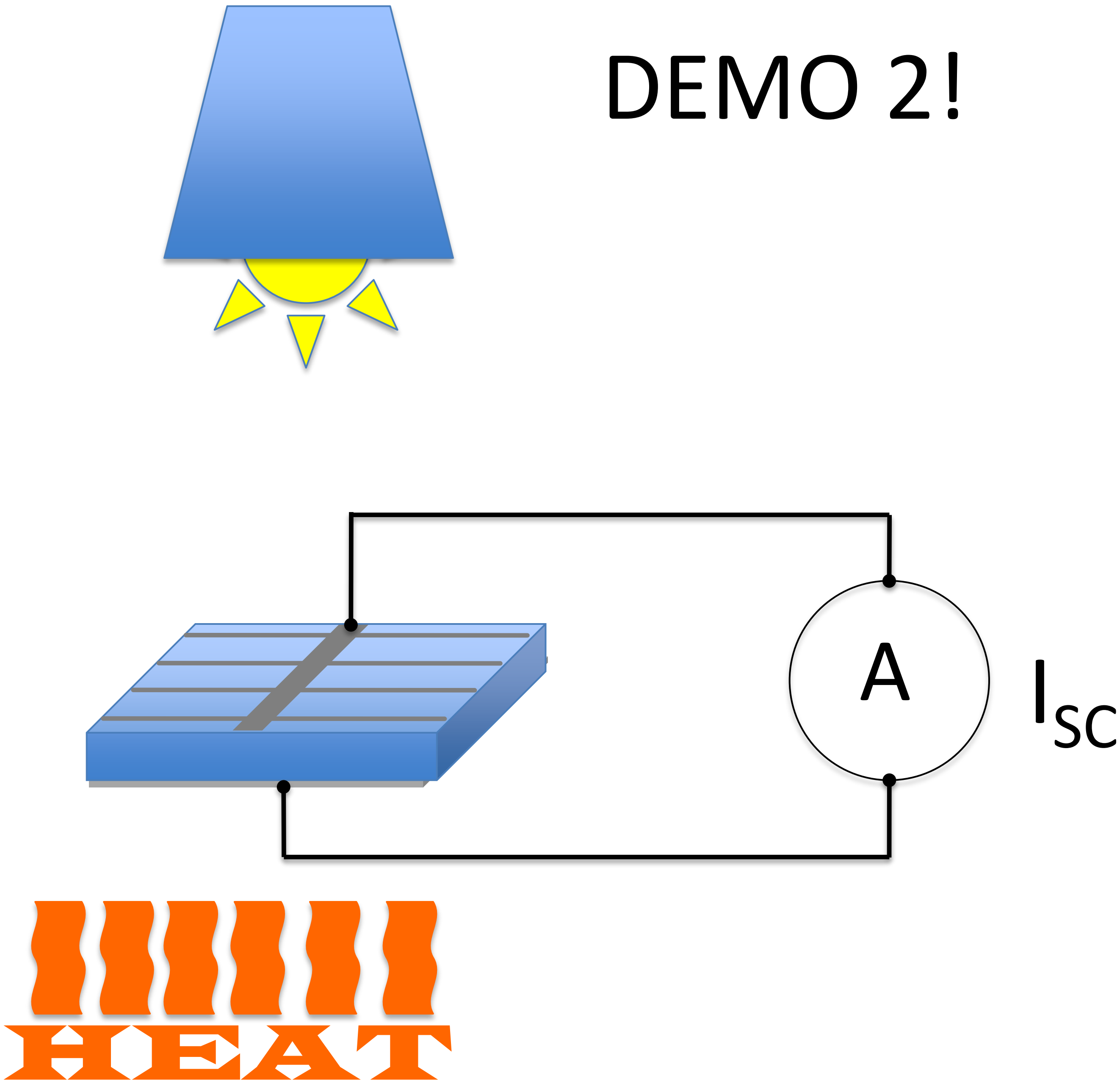
Recall:

$$I = I_L - I_0\left(\exp\left(\frac{qV}{kT}\right) - 1\right)$$

$$I_0 = \frac{qADn_i^2}{LN_D}$$

What do you think will happen with I_{SC} with temperature?

DEMO 2!



I_{SC} increases with Temperature

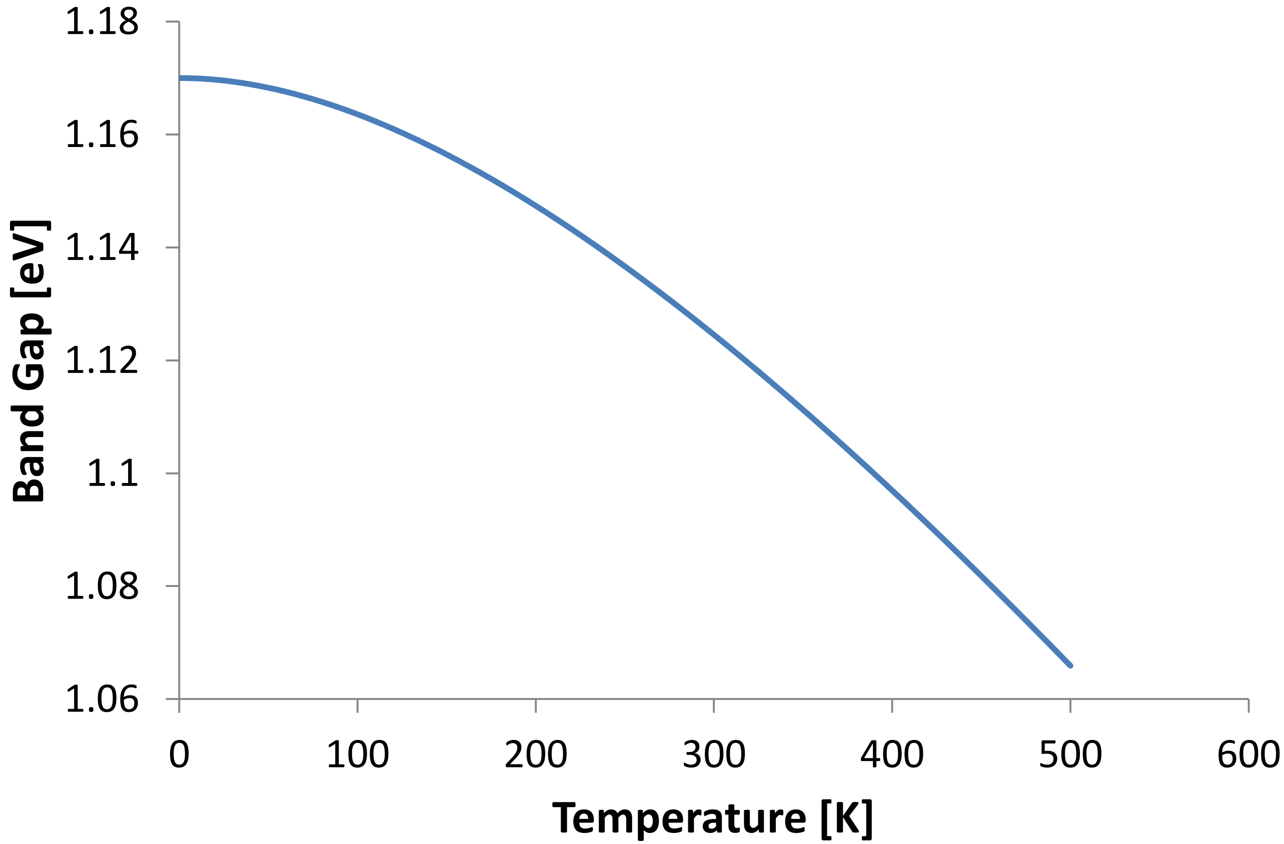
- Recall:
  - $I_{SC} \approx I_L$
- IL increases with the flux of photons of energy greater than the E_G.
- E_G decreases with increased temperature.

$$\frac{1}{I_{SC}} \frac{dI_{SC}}{dT} \approx 0.0006 \; per \; {}^{o}C \; for \; Si$$

VERY SMALL EFFECT!

Source: PV CDROM

Band Gap Dependence on Temperature



Temperature Decreases Overall Efficiency

$$\frac{1}{P_M}\frac{dP_M}{dT} = \frac{1}{V_{OC}}\frac{dV_{OC}}{dT} + \frac{1}{FF}\frac{dFF}{dT} + \frac{1}{I_{SC}}\frac{dI_{SC}}{dT}$$

$$\frac{1}{FF}\frac{dFF}{dT} \approx \left(\frac{1}{V_{OC}}\frac{dV_{OC}}{dT} - \frac{1}{T}\right) \approx -0.0015\ per\ \ ^{o}C\ for\ Si$$

$$\frac{1}{P_M}\frac{dP_M}{dT} \approx -(0.004\ to\ 0.005) per\ \ ^{o}C\ for\ Si$$

Courtesy of PVCDROM. Used with permission.

η decreases ~ 0. 5% per °C for Si

Green, M. A., "Solar cell fill factors: General graph and empirical expressions", Solid-State Electronics, vol. 24, issue 8, pp. 788 - 789, 1981.

Source: PV CDROM

Effect of Light Intensity (*C*)

To first order:

Linear dependence of I_{sc} on *X*: $$I_{sc} = C \cdot I_L$$

Log dependence of V_{oc} on *X*: $$V_{oc} \approx \frac{k_B T}{q} \ln\left(\frac{C \cdot I_{sc}}{I_o}\right)$$

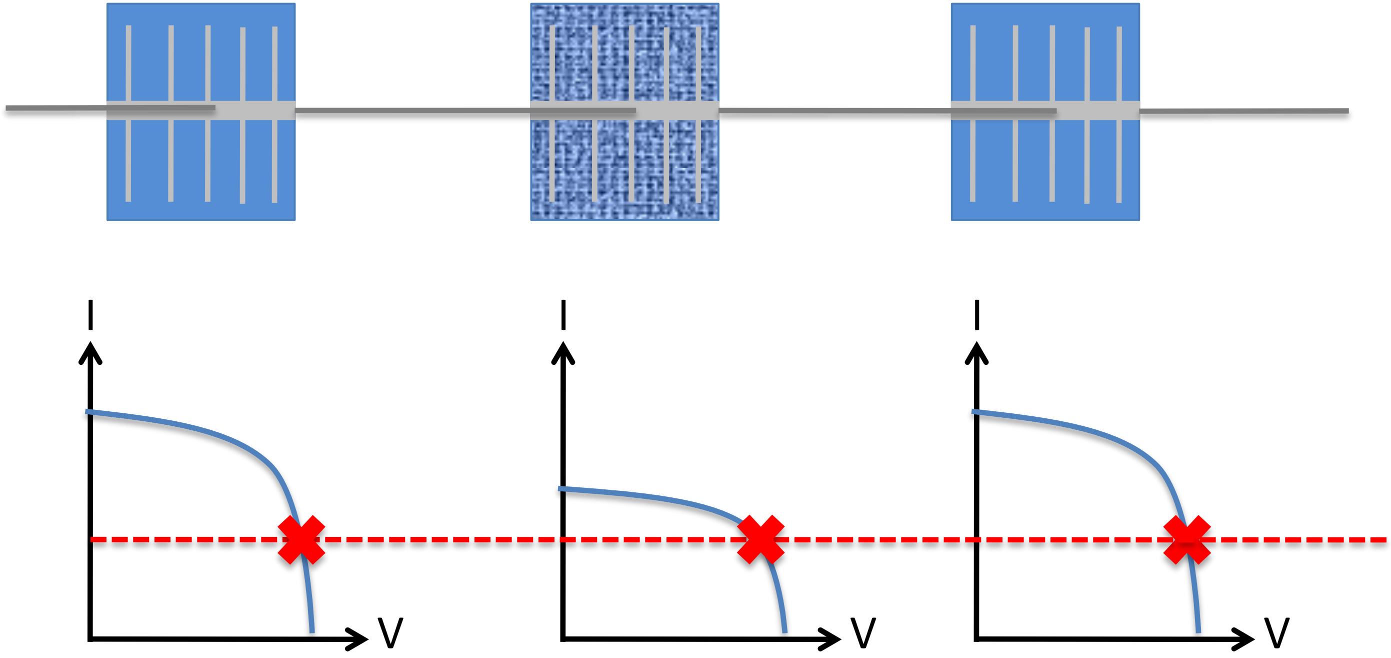
Dependence of Efficiency: $$\eta \propto J_{sc} V_{oc} \propto C \ln(C)$$

Beware the increased impact of series resistance!

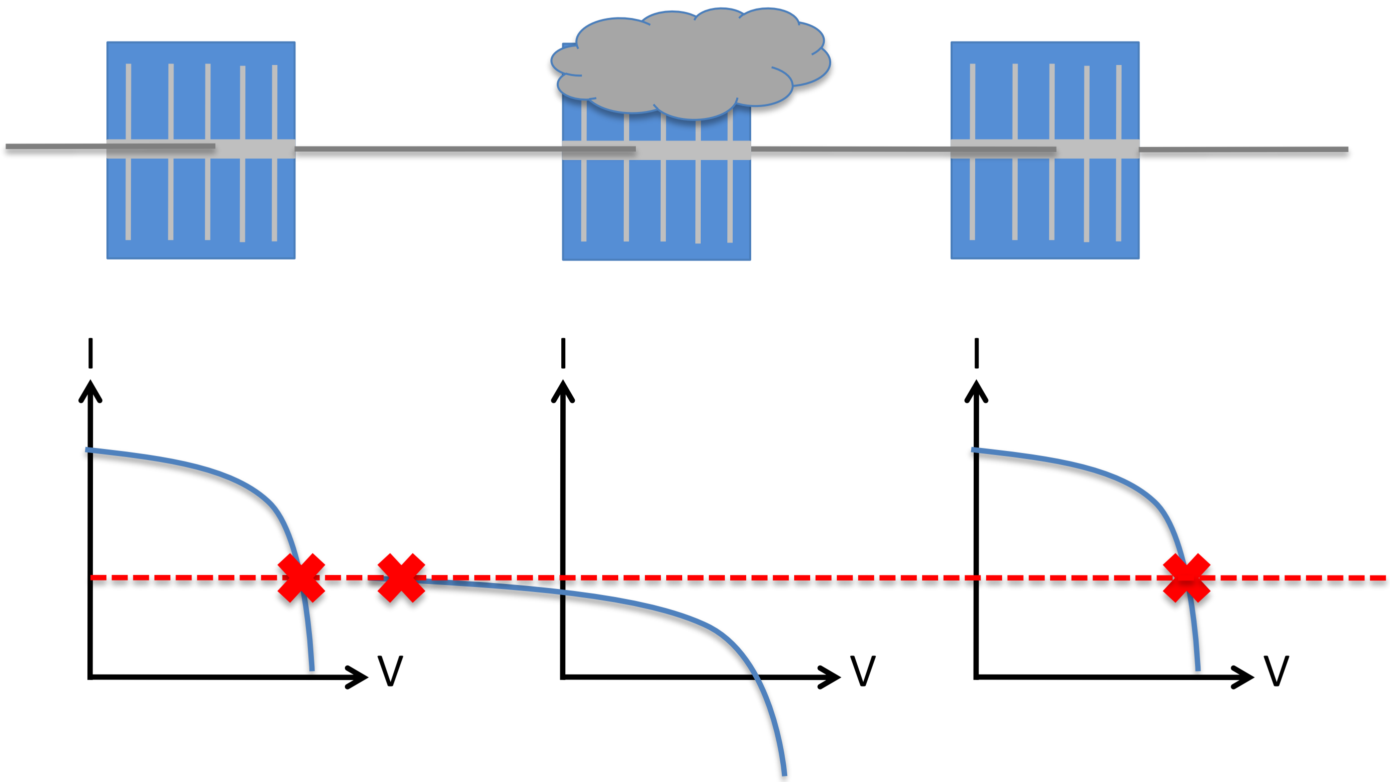
In-class example: http://www.pveducation.org/pvcdrom/solar-cell-operation/effect-of-light-intensity

Module vs Cell Efficiency

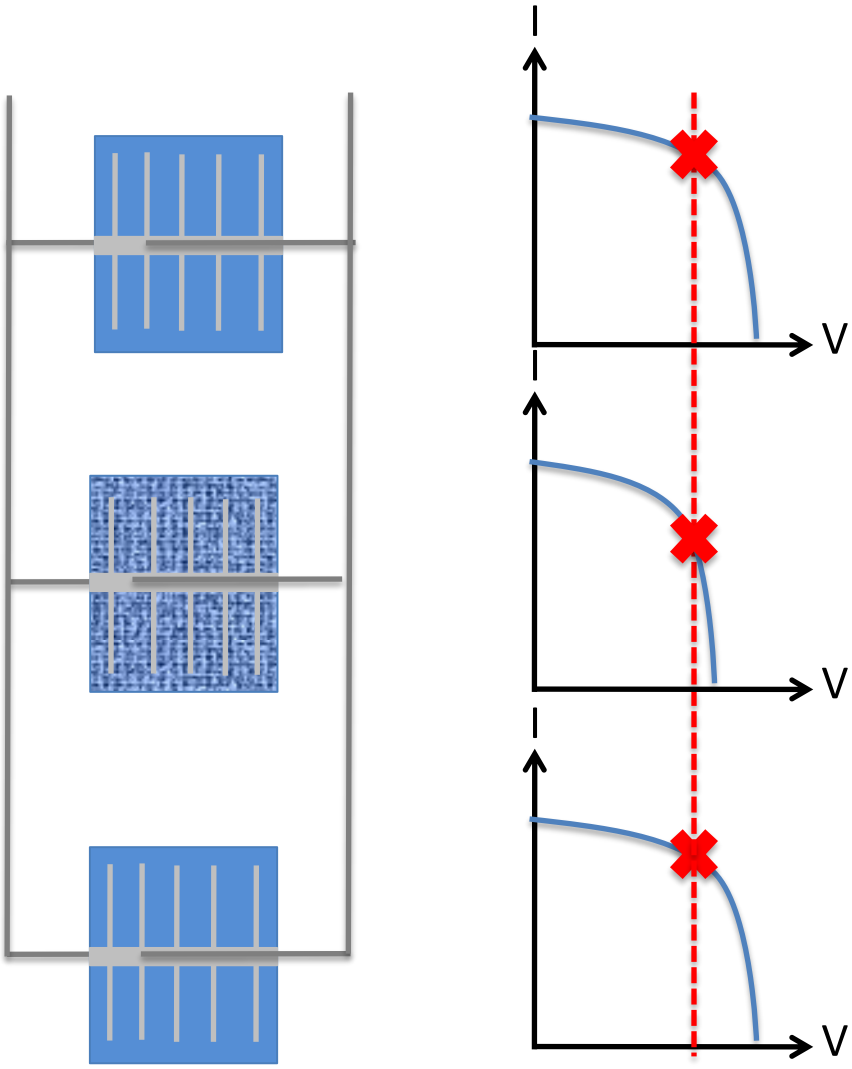
Cells in **Series** in a Module are matched by cell with the lowest current. Voltages add.



Effect of Shading



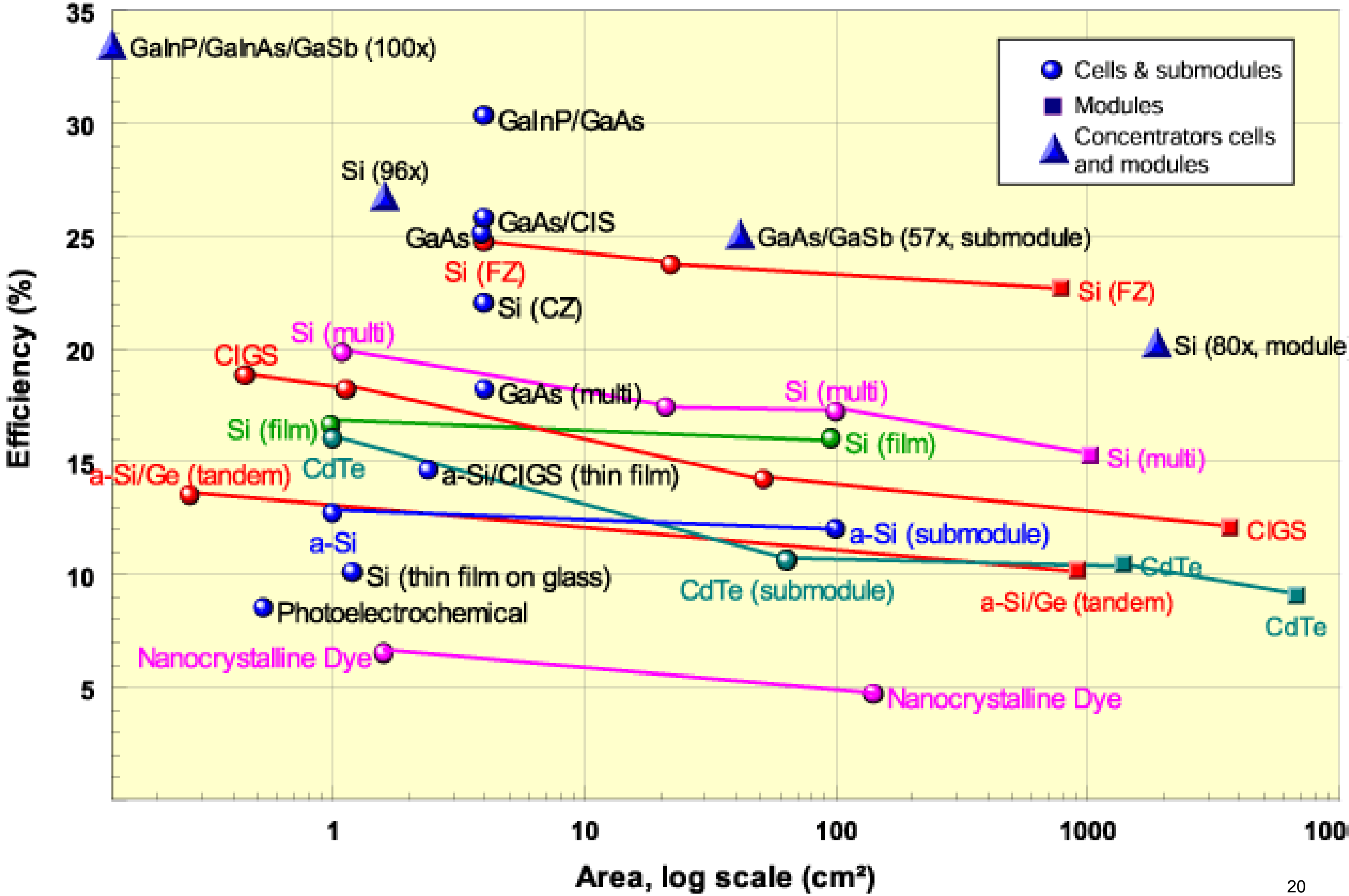
Module vs Cell Efficiency



Cells in **Parallel** in a Module are matched in voltage.

Currents add.

Effect of Inhomogeneities



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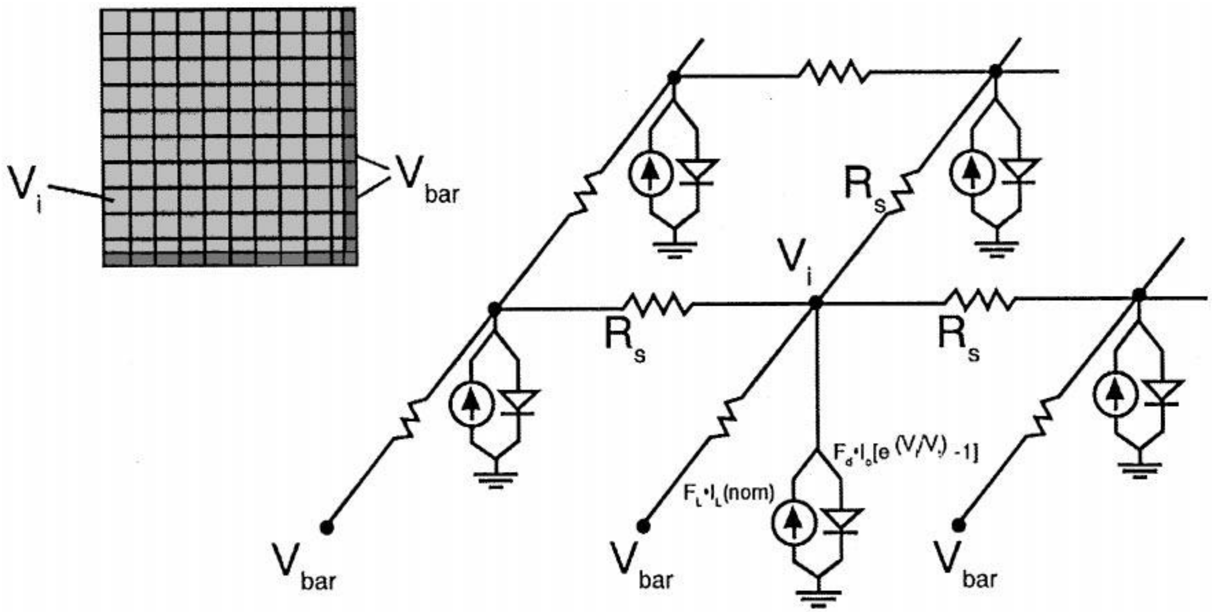
Source: PV CDROM

Effect of Inhomogeneities

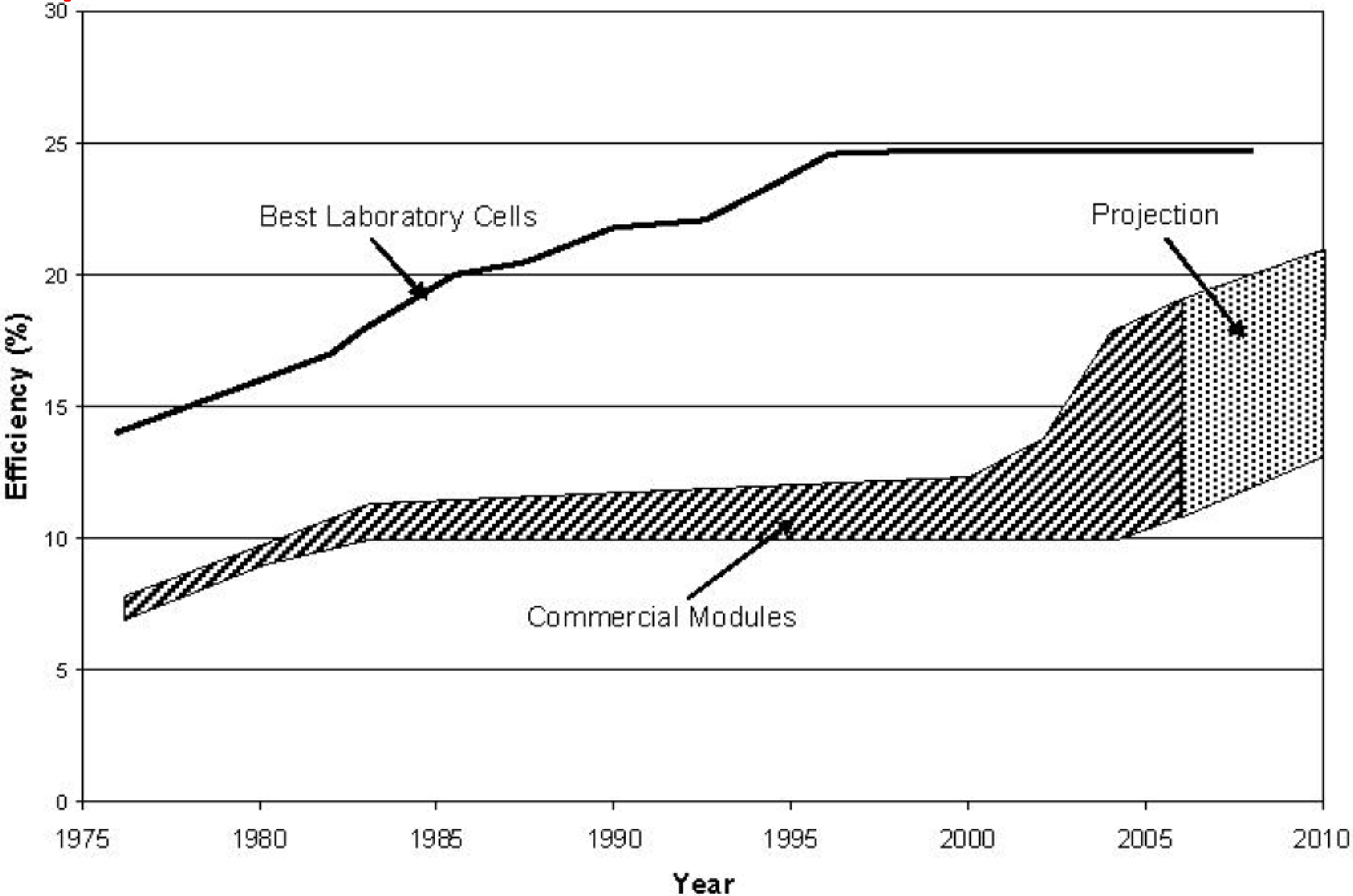
Larger samples tend to have greater inhomogeneities.
→ "Good regions" and "bad regions" connected in parallel.



Courtesy of Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

B.L. Sopori and W. Chen, *J. Cryst. Growth* **210**, 375 (2000)

Gap Between Record Cells and Modules



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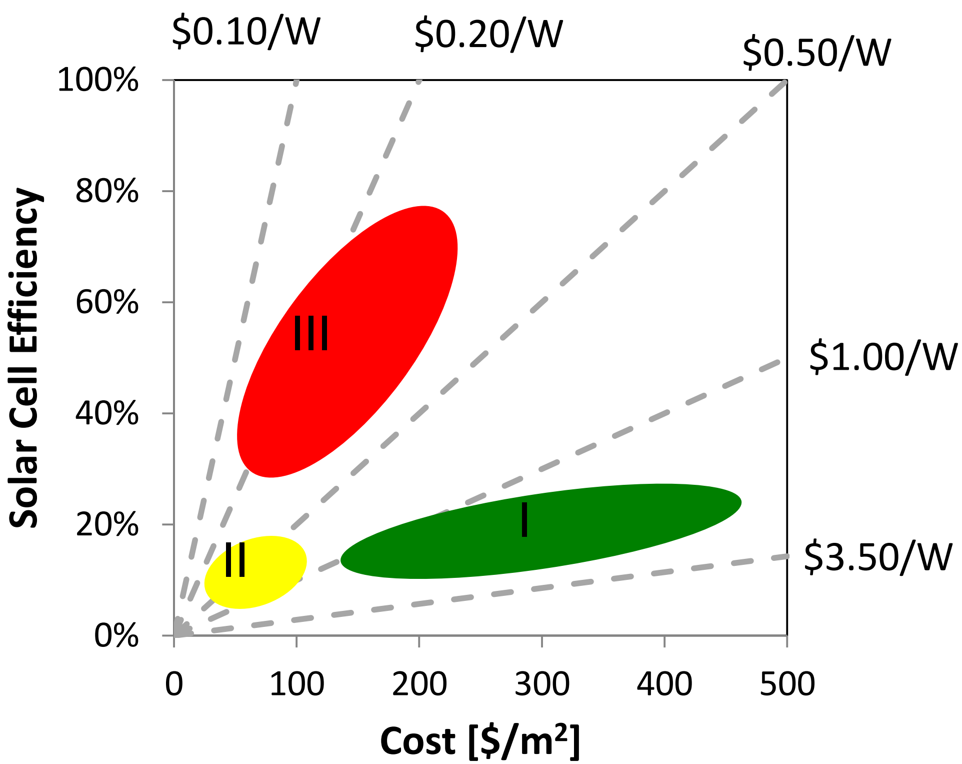
Source: Fig. 6 in Swanson, Richard M. "Developments in Silicon Solar Cells." *Proceedings of the IEEE International Electron Devices Meeting* (2007): 359–62.

Richard M. Swanson (SunPower)

Advanced Concepts

Third Generation Solar Cells



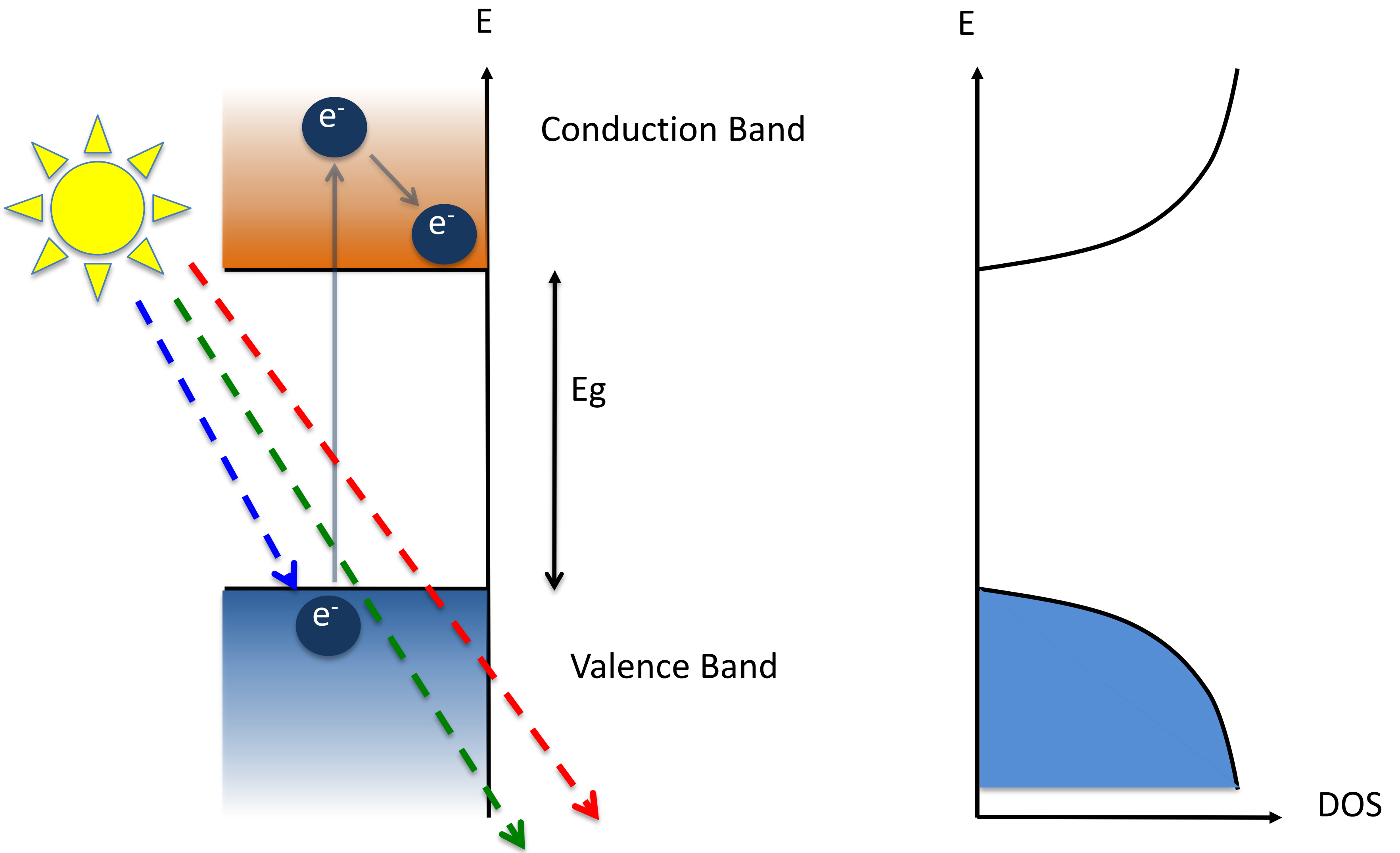
- 1st gen = single bandgap
  - High cost
  - 15-20% efficient
- 2nd gen = thin films
  - Low cost
  - 8-14% efficient
- 3rd gen = advanced concepts
  - Low cost
  - >25% efficiency

$$\$/W = \frac{\$/m^2}{\Phi(\frac{W}{m^2}) \cdot \eta \cdot Y}$$

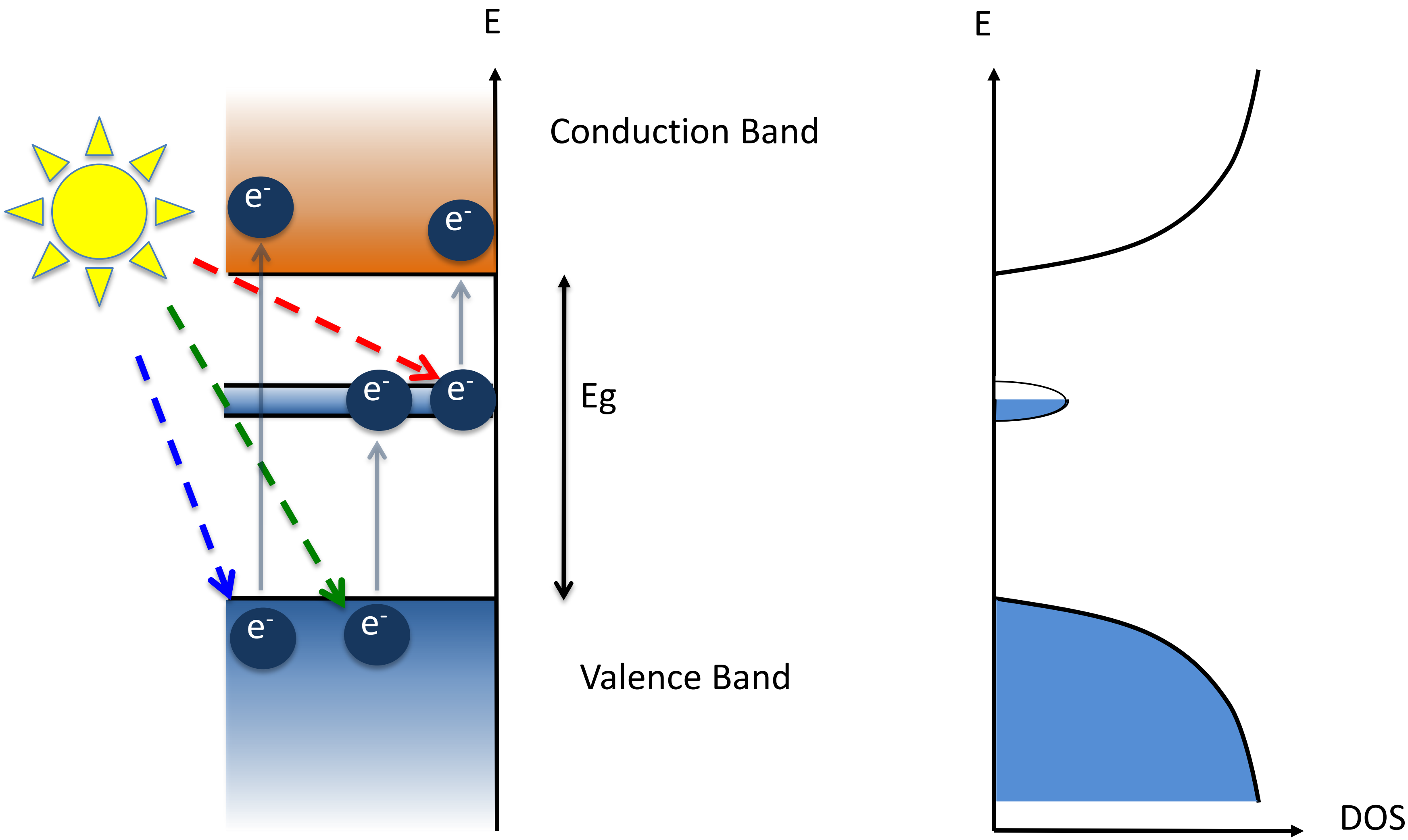
"Third Generation Photovoltaics", Materials Review v10 (2007)

Intermediate Band Materials

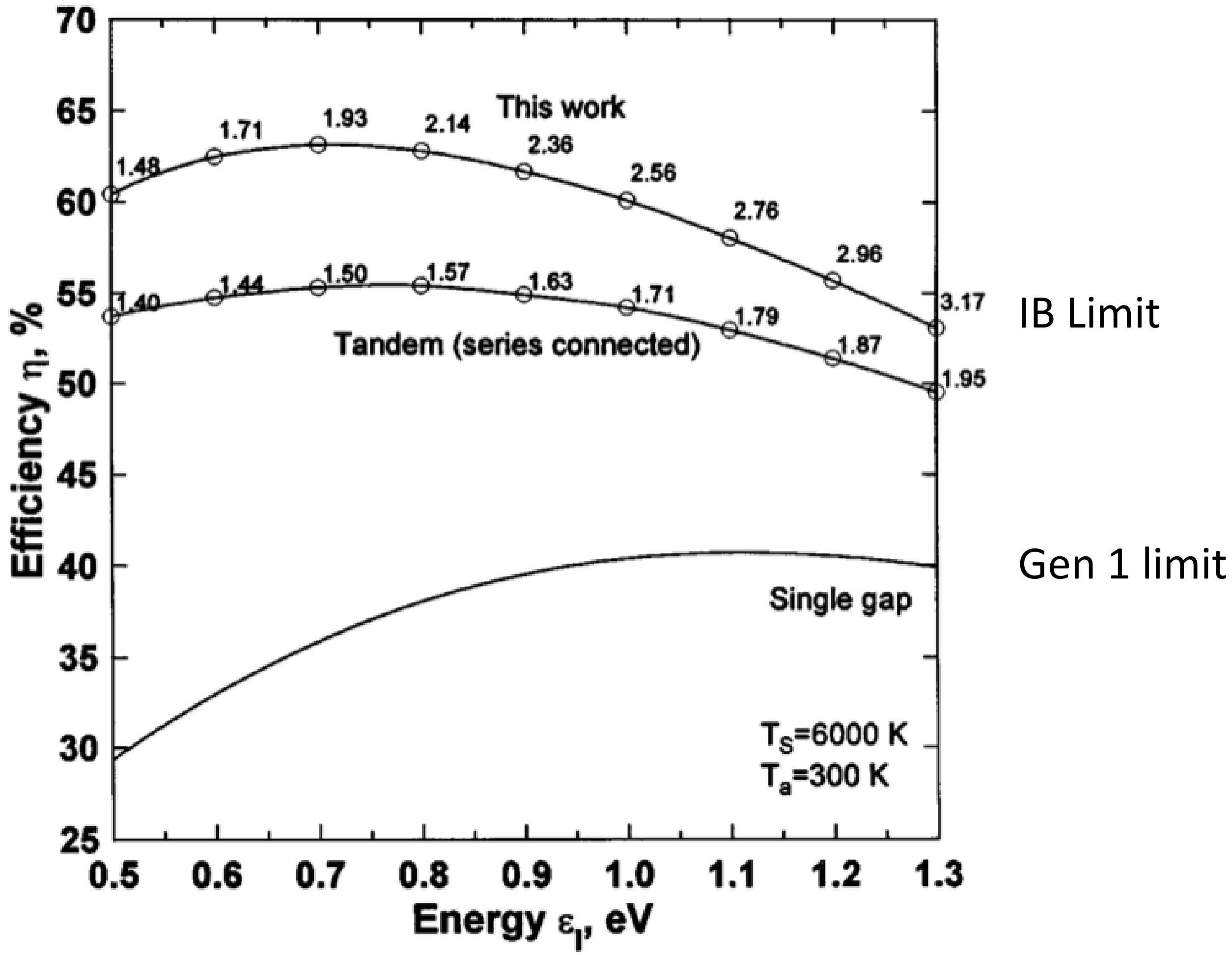
Absorption of Photons in a Semiconductor



Added Absorption Pathway in IB Semiconductor



Theoretical Efficiency Gain From IB Solar Cells[1]



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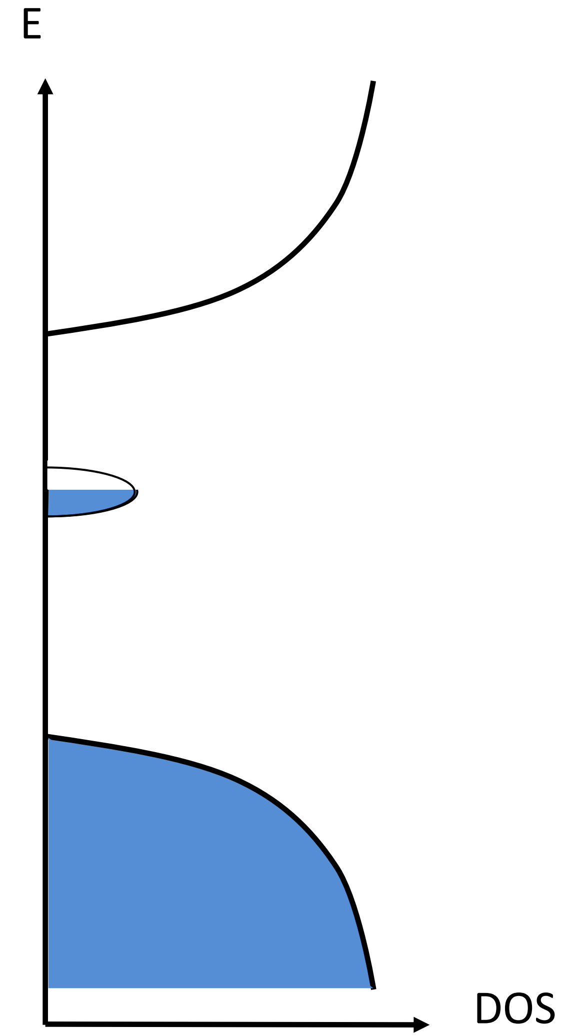
Source: Luque, A. and A. Marti. "Increasing the Efficiency of Ideal Solar Cells by Photon Induced Transitions and Intermediate Levels." *Phys. Rev. Lett.* 78, no. 26 (1997): 5014-7.

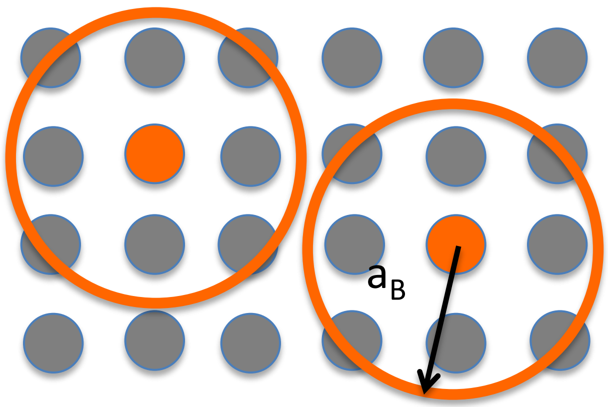
How to Create an IB?

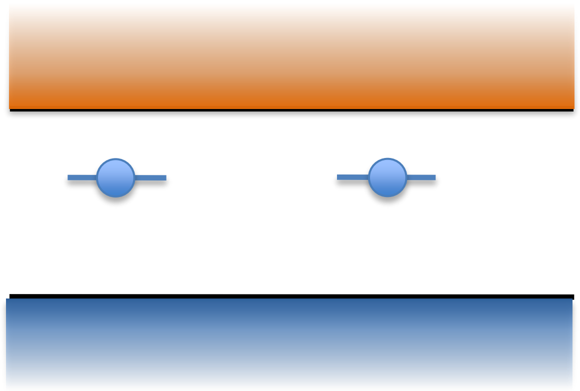
- Three approaches:
  - Impurity band
  - Highly-mismatched alloys (Band Anti-crossing)
  - Quantum dot arrays



Impurity Band

$N_D < N_{crit}$



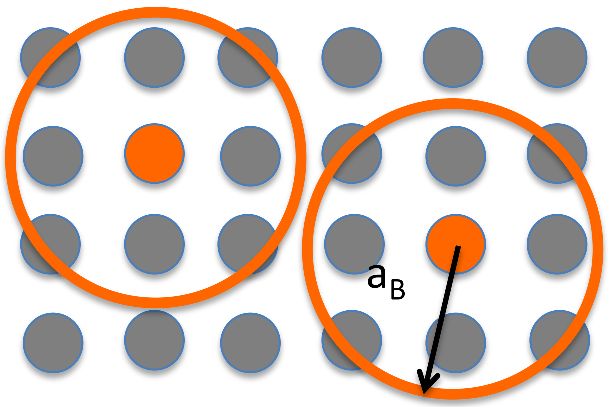


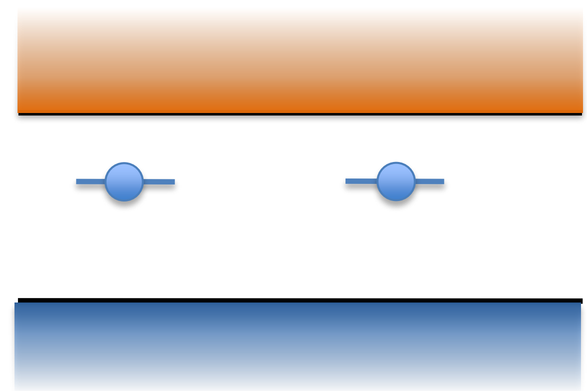
[1] A. Luque, A. Martí, E. Antolín, and C. Tablero, *Physica B* **382**, 320 (2006)
[2] A. Luque and A. Martí, *Solid State Phenomena* **156-158**, 107 (2010)

Impurity Band

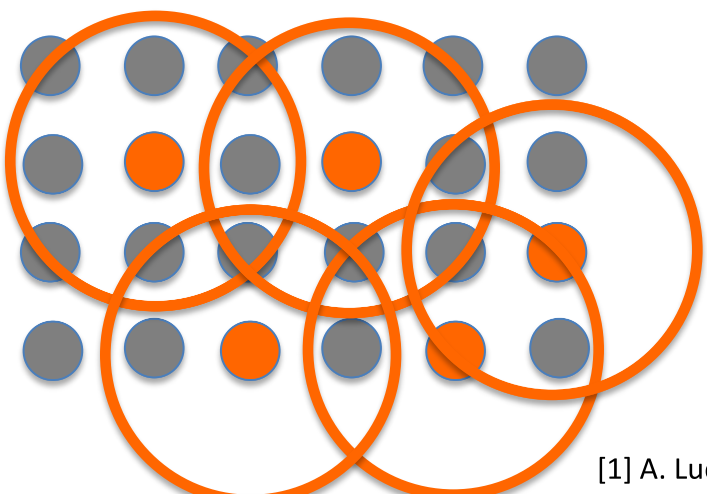
$$N_{crit}^{1/3} * a_B \sim 0.26$$

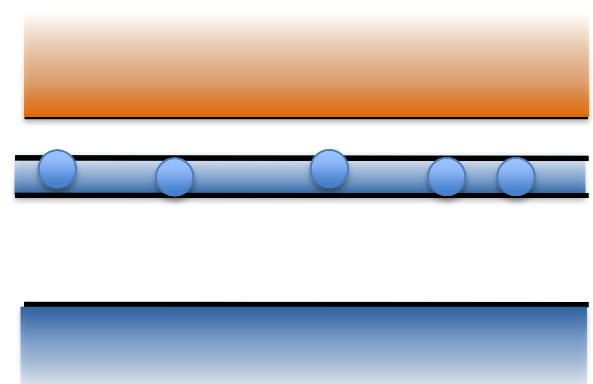
$N_D < N_{crit}$





$N_D > N_{crit}$





[1] A. Luque, A. Martí, E. Antolín, and C. Tablero, *Physica B* **382**, 320 (2006)

[2] A. Luque and A. Martí, *Solid State Phenomena* **156-158**, 107 (2010)

Quantum Dot/Well

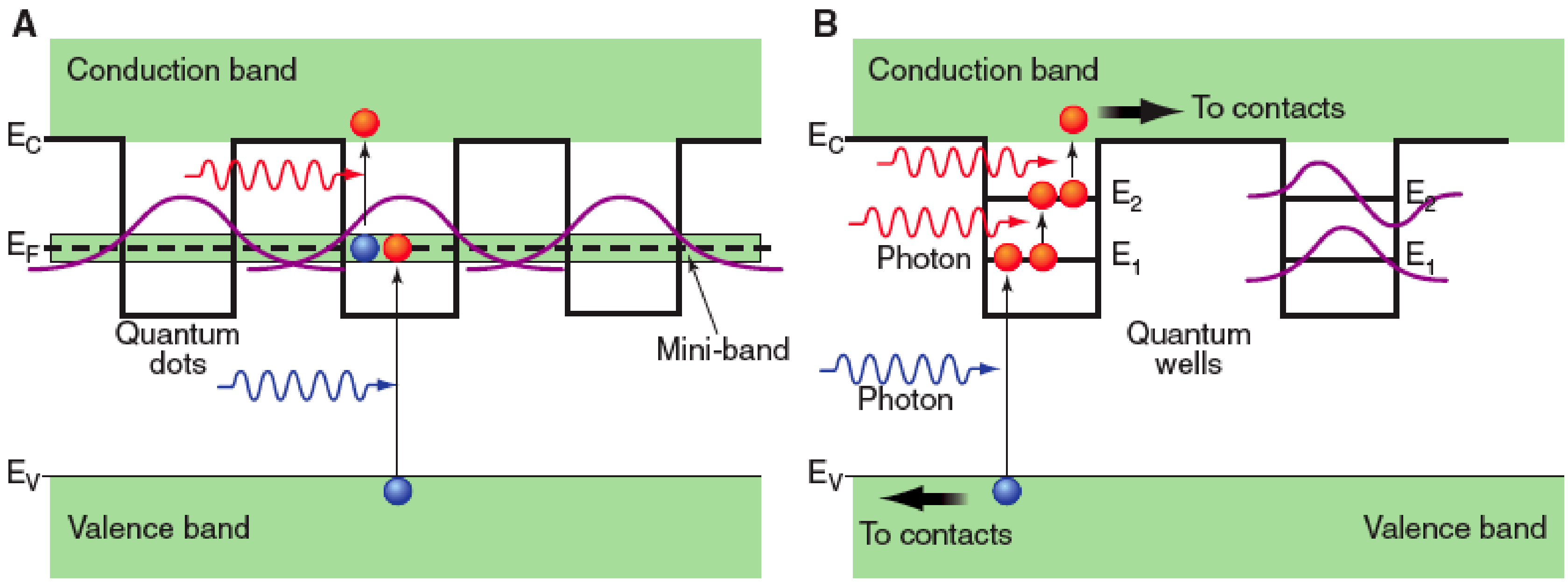


Fig. 2. Possible methods of circumventing the 31% efficiency limit for thermalized carriers in a single–band gap absorption threshold solar quantum conversion system. (**A**) Intermediate-band solar cell; (**B**) quantum-well solar cell. [Adapted from (*2*)]

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Source: Fig. 2 in Lewis, Nathan. "Toward Cost-Effective Solar Energy Use." *Science* 315 (2007): 798-801.

N. Lewis, *Science* **315** (2007) 798

Band-Anticrossing

Please see lecture 15 video or the references below for relevant band diagram visuals.

Yu et al. “Diluted II-VI oxide semiconductors with multiple band gaps.” *Phys. Rev. Lett.* 91, no. 24 (2003): 246403.

López et al. “Engineering the Electronic Band Structure for Multiband Solar Cells.” *Phys. Rev. Lett.* 106, no. 2 (2011): 028701.

Hot Carrier Cells

Hot carrier cells

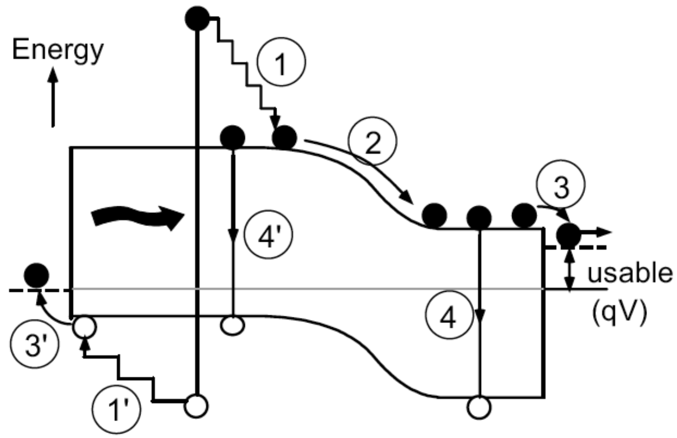

Fig. 1. Loss processes in a standard solar cell: (1) thermalisation loss; (2) and (3) junction and contact voltage loss; (4) recombination loss.

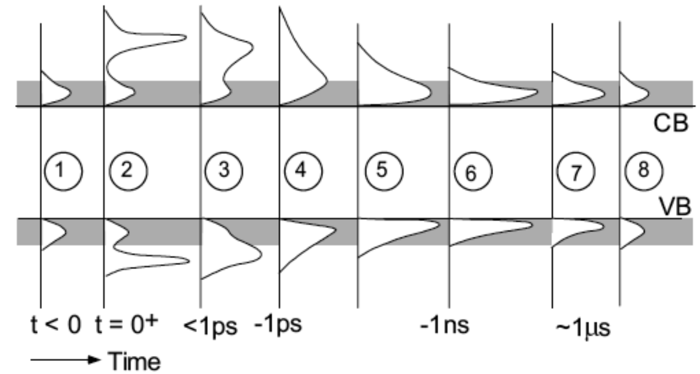

Fig. 4. Energy relaxation of carriers after a short, high-intensity laser pulse at $t = 0$.

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M.A. Green, *Physica E* **14** (2002) 65

- Thermalization (pathway 1, left) accounts for a large efficiency loss, especially in small-bandgap materials.
- Hot carrier cells aim to collect carriers before they decay from an excited state. Carriers either move very quickly, and/or are inhibited from decaying. Band structure and contacts must also be properly designed.
- Theoretical efficiency limit for hot carrier cell: 86.8%.

Challenges:

- Practical implementation difficult.
- Must compete with highly-efficient processes (e.g., thermalization).

Hot carrier cells

Approach #1: Slow Carrier Cooling (e.g., by interruption of phonon modes)

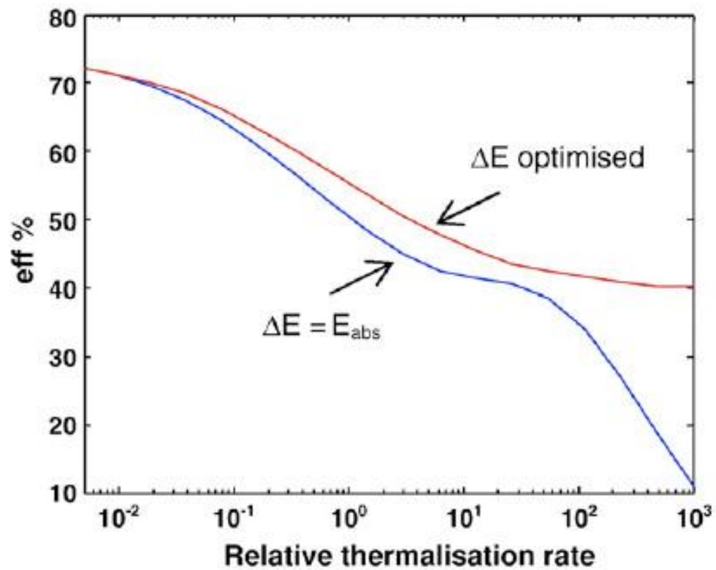

Fig. 7. Dependence of hot carrier cell efficiency on thermalisation rate. A rate of 1 corresponds to that measured in GaAs quantum wells [15,16]. In addition the importance of optimising the extraction energy ΔE is emphasised.

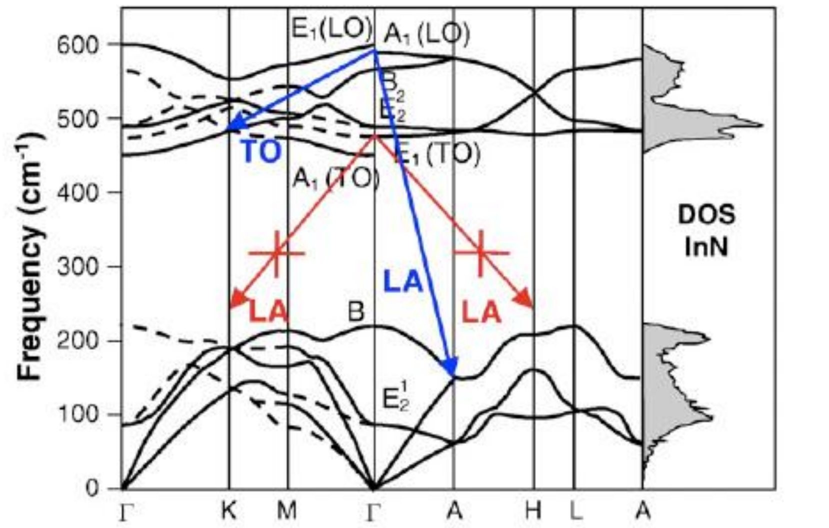

Fig. 3. Phonon energy as a function of phonon momentum and density of states (DOS) for InN redrawn from [12] in which $E_{LO} > 2E_{LA}$ such that LO→2LA (Klemens mechanism) is forbidden, whereas the LO→TO+LA (Ridley mechanism) can occur, although it is normally less likely and involves smaller loss of energy [13].

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Goal: To slow carrier cooling by modifying material parameters and geometry, to prolong excited charge states in the conduction band.

G.J. Conibeer et al., *Thin Solid Films*. **516**, 6948 (2008)

Hot carrier cells

Approach #2: Selective Energy Contacts

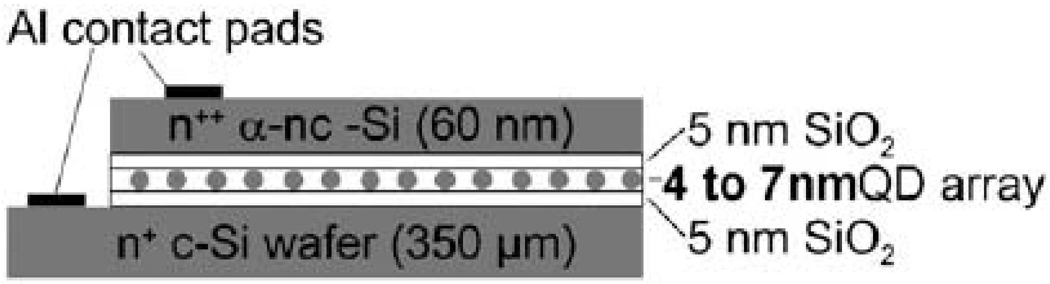

Fig. 3. Sample structure for SEC experiments.

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G.J. Conibeer et al., *Thin Solid Films* 516 6968 (2008)

Goal: To extract hot carriers from devices, e.g., via resonant tunneling contacts.

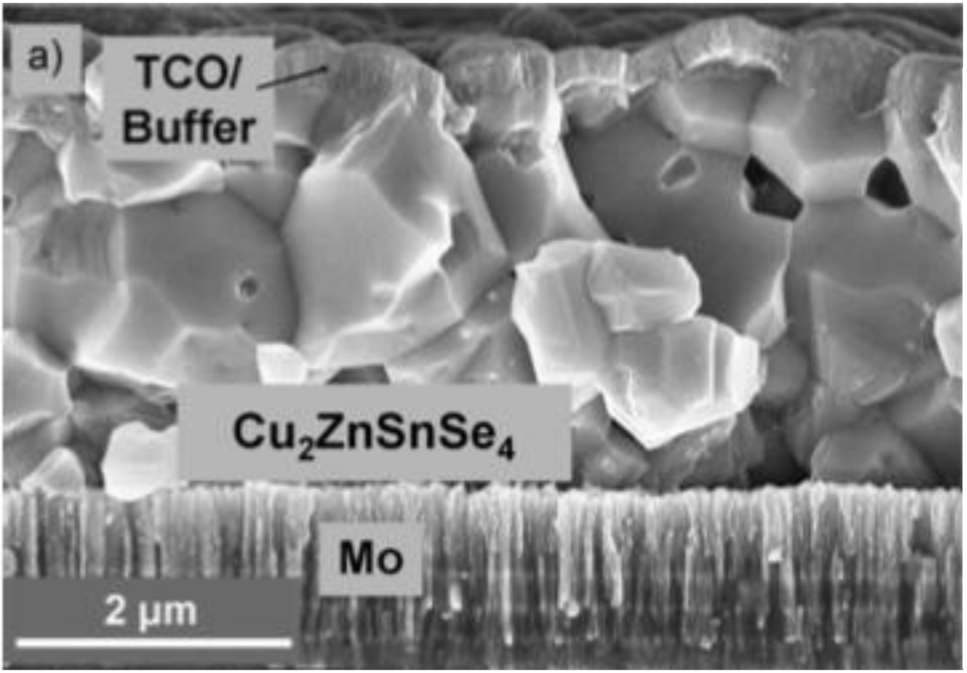
Emerging Tech: Bulk Thin Films

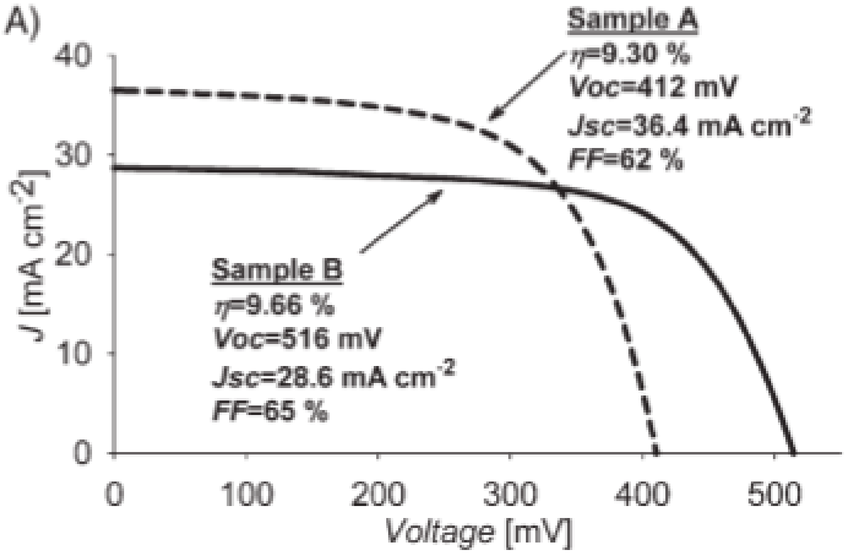
Last Classes: Summary of the Most Common Commercial and Nearly-Commercial PV Technologies

		Common Deposition/Growth Method	Sample Companies	Typical Commercial Cell Efficiencies
Wafer-Based	Monocrystalline Silicon (sc-Si)	Czochralski (CZ)	SunPower, REC, Sanyo…	18-22%
	Multicrystalline Silicon (mc-Si)	Directional solidification (Bridgman)	Q-Cells, Suntech, REC, Solarworld…	16-17.5%
	Ribbon Silicon	String Ribbon (SR)	Evergreen Solar, Sovello…	~15.5%
Thin Film	Cadmium Telluride (CdTe)	Chemical vapor deposition (CVD) on glass	Pureplays (First Solar)	~11%
	Amorphous Silicon (a-Si) and variants	Plasma-enhanced chemical vapor deposition (PECVD) on glass or metal substrates	Pureplays (Energy Conversion Devices) Turnkey System Manufacturers (Oerlikon)	~6-9%
	Copper Indium Gallium Diselenide (CIGS)	Variety: CVD, physical vapor deposition (PVD) on glass, metals.	Start-ups (Nanosolar, Heliovolt)	Pre-commercial: 6-14% reported.

Finding Earth-Abundant Thin Films

- CuInGaSe$_2$
  - Alternative: $Cu_2ZnSnSe_4$ (CZTS)





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Todorov et al. High-Efficiency Solar Cell with Earth-Abundant Liquid-Processed Absorber. *Adv. Mater*. **22**, E156-E159 (2010).

D. Mitzi *et al*., "The path towards a high-performance solution-processed kesterite solar cell," *Solar Energy Materials and Solar Cells*, in press (2011).

Materials Availability Limits Many PV Materials

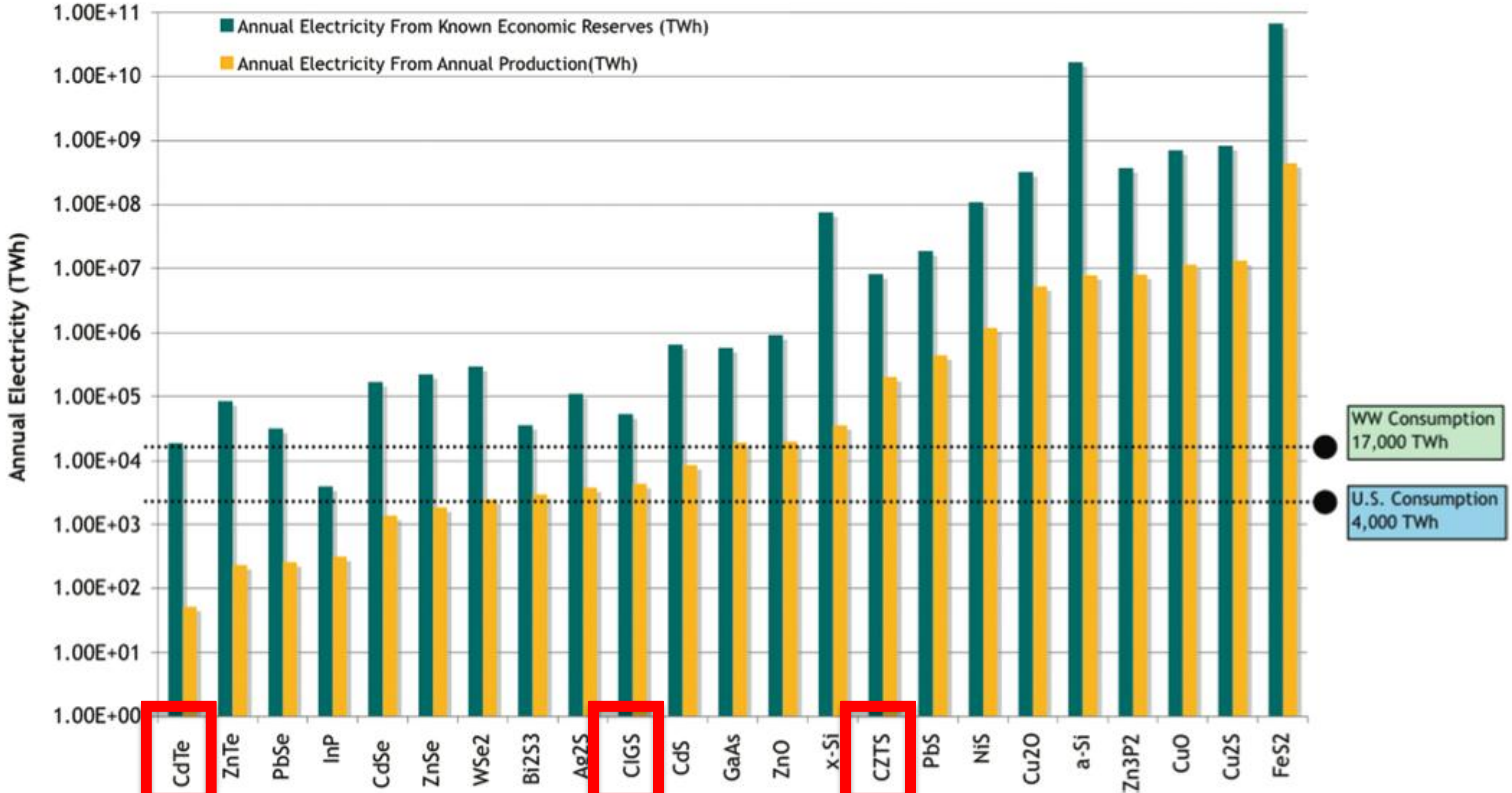

FIGURE 1. Annual electricity production potential for 23 inorganic photovoltaic materials. Known economic reserves (also known as Reserve Base) and annual production are taken from the U.S. Geological Survey studies (*21*). Total U.S. and worldwide annual electricity consumption are labeled on the figure for comparison.

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Wadia et al. Materials availability expands the opportunity for large-scale photovoltaics deployment. Environmental science & technology (2009) vol. 43 (6) pp. 2072-2077

Raw Material Costs

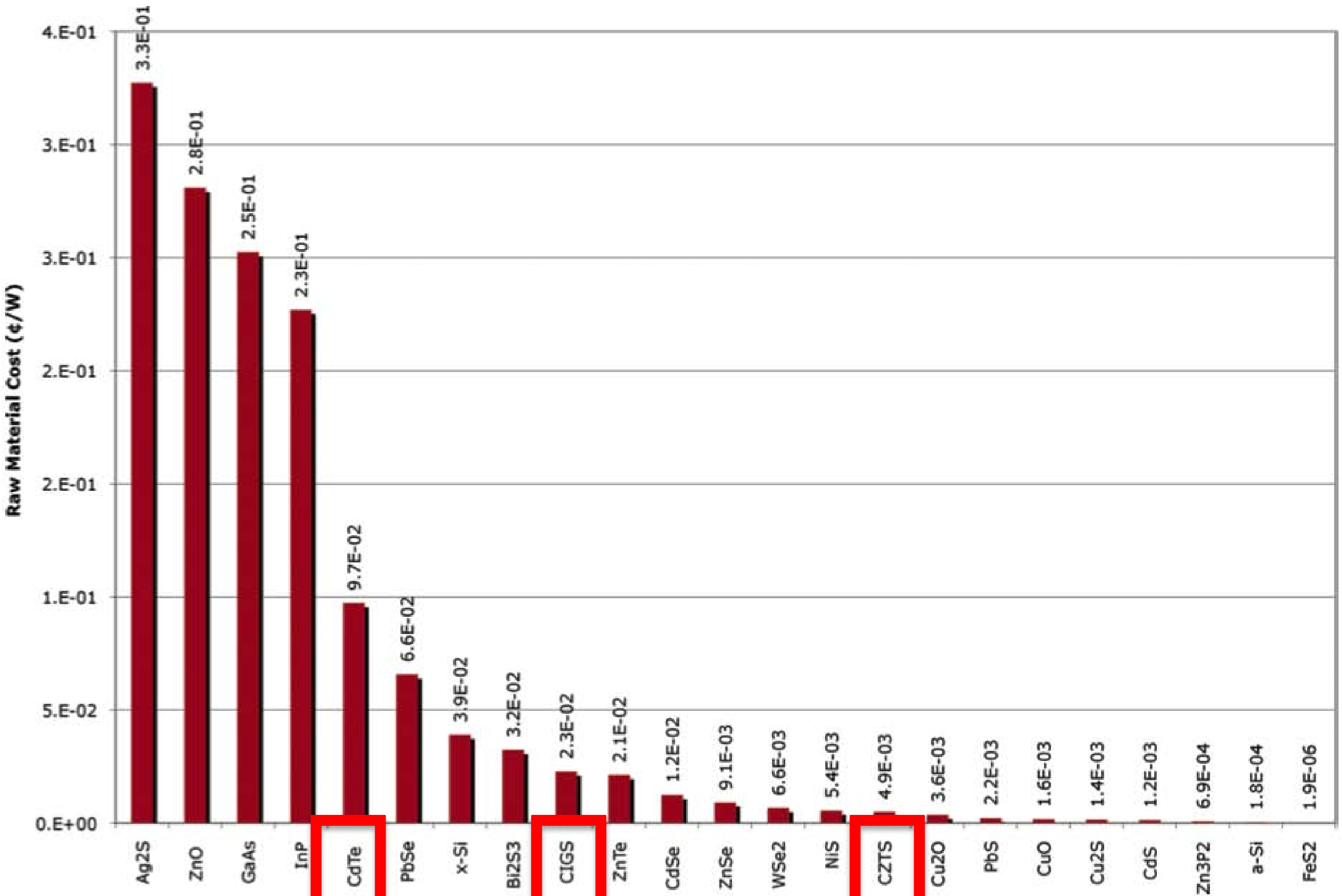

FIGURE 2. Minimum ¢/W for 23 inorganic photovoltaic materials. Component cost contribution in ¢/W is a strong indicator of value for future deployment. Calculated values for all 23 compounds evaluated are shown. The range of costs are between 0.327¢/W for Ag_2S and <0.000002¢/W for FeS_2. While the actual dollar figure per watt for material extraction will appear small compared to the entire cost of an installed PV system, the cost of processing the material for PV grade applications is a larger cost contributor and should be evaluated further.

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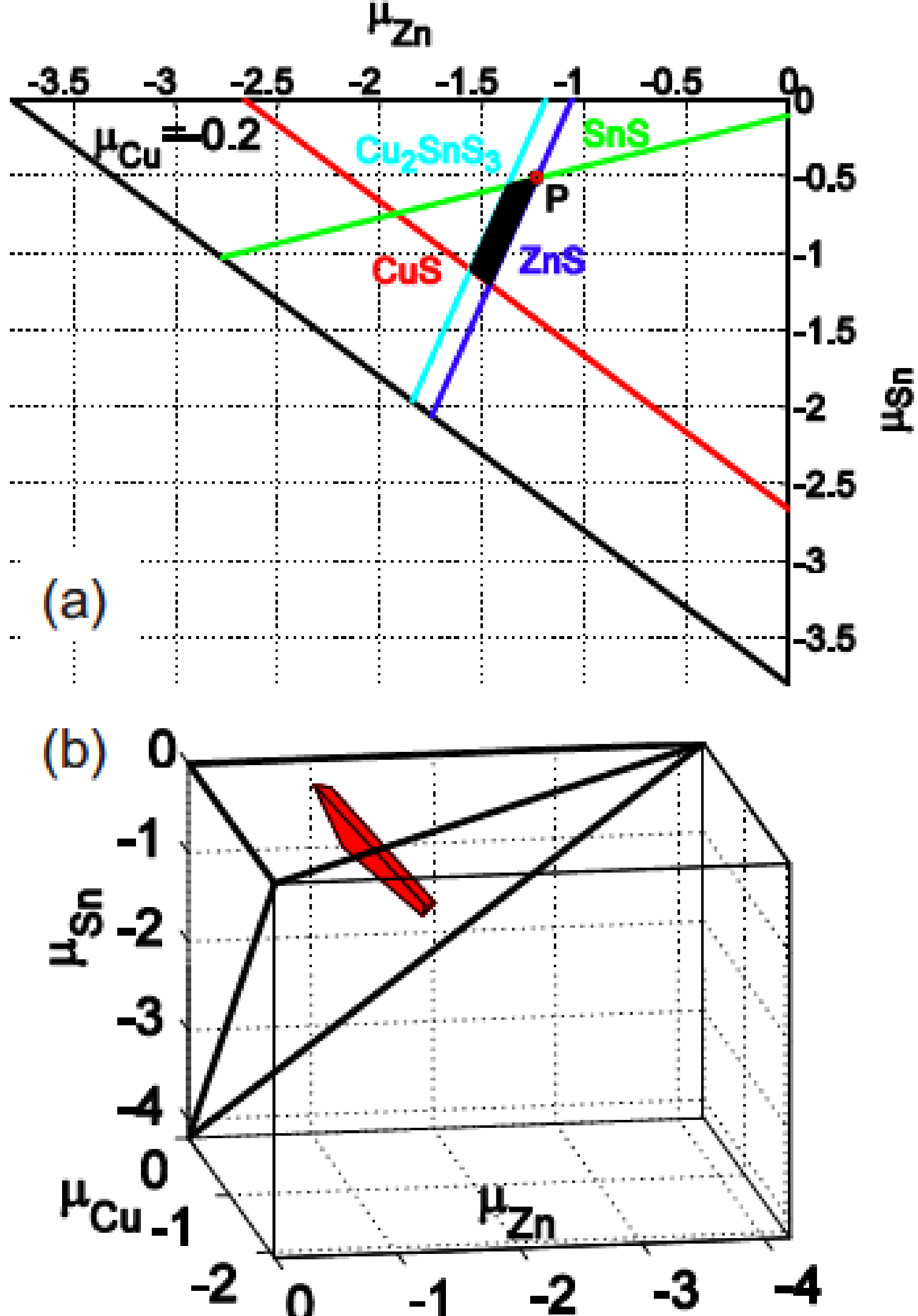
Confined Parameter Space

Many challenges in developing new materials. Obtaining right stoichiometry is key!



S. Chen *et al.*, *Appl. Phys. Lett.* **96**, 021902 (2010)

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